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PRELIMINARY RESULTS OF TESTING A SINGLE-TUBE POTASSIUM BOILER FOR THE ADVANCED RANKINE SYSTEM

by Martin U. Gutstein
Lewis Research Center
Cleveland, Ohio

and

James A. Bond
General Electric Company
Cincinnati, Ohio

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ABSTRACT

In support of the technology for the advanced Rankine system, a nuclear electric power plant for space, a program was conducted to test a lithium-heated single-tube potassium boiler at exit saturation temperatures as high as 1420 K. A sample of the results obtained, including a temperature distribution in the boiler, the variation of boiler pressure losses with potassium flow rate, and average potassium boiling heat transfer coefficients for a range of exit qualities and exit superheats, is presented. One transient test, simulating the startup of the advanced system, is described. The success of the boiler testing represents a major advance in the technology for high-temperature liquid-metal space power systems.

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Martin U. Gutstein, NASA-Lewis

and

James A. Bond, General Electric Co.*

Lewis Research Center

SUMMARY

A major component of the advanced Rankine system is the potassium boiler. To develop the technology for this component, a 400 kW_t-capacity, refractory-alloy test facility was built consisting of a lithium-heating loop, a potassium-boiling loop and a NaK heat-rejection loop. A single-tube boiler was installed in this facility and tested over a wide range of conditions, including boiler exit saturation temperatures of up to 1420 K. A sample of the data and results obtained in this test is presented herein. Included is a temperature profile within the boiler at a condition closely matching the design operating point of the advanced system. Overall pressure losses are shown to increase substantially when the boiler operates with a modest exit superheat. The average potassium-boiling heat-transfer coefficients, at exit saturation temperature levels of 1255 and 1380 K, are relatively large but decrease as the boiler produces superheated vapor at the exit. One of the transient tests that were conducted, a simulation of the startup of the advanced system to a self-sustaining condition, is likewise discussed. The results of the testing of this boiler mark an advance in the technology for high-temperature liquid-metal space power systems.

INTRODUCTION

About 1960, the National Aeronautics and Space Administration undertook the development of technology for high-temperature liquid-metal space electric power systems because of the potential need for such devices for advanced missions. The advanced Rankine system, a nuclear power plant based on the conventional Rankine thermodynamic cycle but employing potassium as the working fluid, was one such technology selected for development. This system was chosen because, at the very large power levels

* Nuclear Systems Programs, General Electric Co., Cincinnati, Ohio

(hundreds of kilowatts to megawatts), it offered (and still offers) the lowest specific weight and smallest radiator area of all the candidate space electric systems.

One of the major components of the advanced Rankine system is the boiler. Within this component, heat from the nuclear reactor coolant is transferred to the potassium working fluid, converting the latter from a highly subcooled liquid at the boiler entrance to a slightly superheated vapor at the exit. From the boiler, the potassium vapor flows directly to the turboalternator and then to the condenser where it is restored to the liquid state. The potassium is returned to the boiler inlet by means of a recirculation pump.

System studies (ref. 1, for example) have indicated that potassium boiler inlet and outlet temperatures of about 920 and 1420 K, respectively, would be required. Corresponding temperatures of the reactor coolant, liquid lithium, entering and leaving the boiler would be about 1475 and 1420 K, respectively. In addition, the boiler would have to be compact so as to minimize reactor shield weights. This constraint resulted in a conceptual boiler design consisting of a bundle of tubes, into which the potassium would flow and be vaporized, surrounded by a shell. The lithium would flow in the space between the tubes and the shell, countercurrent to the potassium. If needed, the boiler would be bent into an arc of a circle for packaging into a shielded gallery of the spacecraft.

In order to design the boiler for the advanced Rankine system, a program was undertaken to test candidate single-tube boilers at the required system conditions. A large T-111 (Ta-8W-2Hf) refractory metal facility was constructed, as part of this program, to provide the means for introducing the lithium and potassium fluids into the test boiler at the appropriate temperatures, pressures and flow rates. This facility was put into operation during the fall of 1970 for the purpose of testing the first single-tube boiler. Approximately 200 data runs over a wide range of conditions were successfully obtained with the boiler, including several transient tests, with essentially no instabilities encountered. Each such run consisted of the recording of the output of about 300 instruments such as thermocouples, flow meters and pressure gauges. This mass of data is still in the process of being reduced and analyzed. Pending the completion of this work and its subsequent documentation, this report is issued for the purpose of presenting to the technical community in as timely a manner as possible a small sample of the data obtained and some preliminary heat-transfer results.

DESCRIPTION OF TEST FACILITY

The test facility which was constructed consisted of three interconnected flow circuits. These were a lithium-heating loop, a potassium-boiling loop and a NaK heat-rejection loop. Referring to figure 1, the lithium flows from the electromagnetic (EM) pump through a flow meter, a 400-kW-capacity AC electrical heater and into the shell-side of the single-tube boiler. From the exit of the boiler, the lithium returns to the suction side of the pump for recirculation. Liquid potassium flows from the EM pump through a flowmeter, a liquid throttle valve, a 30-kW-capacity AC electrical preheater and into the tube side of the boiler. Exiting the boiler, the potassium vapor enters a radiant desuperheater and vapor throttle valve, these components acting to simulate the turbine of the advanced system. Expanding through the throttle valve, the vapor then flows into a three-tube condenser. Heat is removed from the vapor and transferred to the condenser coolant, NaK. The potassium in the liquid state returns to the pump for recirculation to the boiler. The NaK coolant flows from an EM pump through a flowmeter and into the shell-side of the condenser. From the condenser, the NaK enters an air cooler and then returns to the pump.

Both the lithium and potassium circuits were fabricated of the tantalum-based refractory alloy, T-111, and were contained in a vacuum chamber about 5.5 meters tall and 1.8 meters in diameter. This chamber is capable of extremely low pressures and is equipped with bake-out heaters and cooling coils. The NaK loop was fabricated of Type 321 stainless steel and is exposed to the ambient. A more detailed description of the test facility is presented in reference 2. An overall view of the vacuum chamber enclosing the lithium and potassium circuits is shown in figure 2.

DESCRIPTION OF SINGLE-TUBE BOILER

A schematic diagram of the test boiler is shown in figure 3. The curved test boiler consisted of an outer and inner tube, both approximately 2.29 meters long, to which were attached appropriate piping fittings for welding into the facility. The inner tube, in which the potassium vaporized, had an outer diameter of 1.91 cm and a wall thickness of 0.102 cm. The outer tube was 3.30 cm in diameter and had a wall thickness of 0.25 cm. The lithium flowed countercurrent to the potassium in the annulus formed by the two tubes. The height of the annulus was nominally 0.445 cm. Slack-diaphragm gauges were attached to the boiler to measure the potassium inlet and outlet pressures.

Thermocouple immersion wells were likewise located near the entrances and exits of the lithium and potassium passages.

Contained within the inner tube was a composite swirl-generating insert for enhancing the heat transfer to the potassium (reference 3). The initial 1.4 meters of the insert consisted of a single helical vane wrapped about and spot-welded to a 0.635-cm-diameter hollow centerbody. The remaining 0.89-meter length of the insert consisted of a helical wire coil. The ratio of pitch (axial distance traversed by the vane or wire coil for a revolution of 2 π radians) to tube-inner-diameter for the composite insert was about 3.0. The centerbody of the helical-vane portion of the insert served as an immersion well into which seven thermocouples were placed for measuring potassium fluid temperatures. Seven additional thermocouples were placed in a similar tube in the region of the boiler which contained the wire coil. Spot-welded to the exterior of the shell-tube was a total of 60 thermocouples, that is, four thermocouples distributed uniformly around the shell periphery at each of 15 axial stations. These were used to measure the lithium-temperature distribution along the length of the boiler. All thermocouples were made from calibrated W-3 Re - W-25 Re wire of 0.012-cm diameter. The boiler was wrapped with ten layers of 0.005-cm-thick dimpled Nb-1 Zr foil for thermal insulation. A more complete description of the test boiler is also given in reference 2.

RESULTS AND DISCUSSION

As described in the INTRODUCTION, approximately 200 tests were conducted with the single-tube boiler. Most of these tests were for the purpose of mapping the steady-state thermal and hydraulic performance of the boiler; however, some transient tests simulating the startup of the advanced Rankine system were also made. For the steady-state tests, Table 1 lists the ranges of the variables which were covered. In the paragraphs below, a small sampling of both the performance and transient test data is presented and discussed.

Temperature Distribution Within Boiler

Figure 4 presents a temperature distribution within the single-tube boiler obtained from the data. The inlet and outlet conditions for this run are given in Table 2. In addition, Table 2 lists the inlet and outlet conditions for the boiler at the nominal design point of the advanced Rankine system (ref. 1). From this table, it is clear that the run shown in figure 4 closely matches the nominal operating condition required for the system.

From the temperature profile shown in figure 4, the liquid, two-phase and superheat regions of the potassium can readily be identified. The liquid region extends from the beginning of the heated zone to a point about 0.15 meter downstream of the inlet. Within this very short length, heat is added to the potassium, raising its temperature to the local saturation temperature of 1387 K. The two-phase or boiling region starts at the 0.15-meter location and extends to about the 1.5-meter point within the heated zone. From the end of this region to the boiler exit is the superheated-vapor region. The characteristic temperature profile shown in figure 4 is identical to the profiles obtained with boiling potassium at exit saturation pressures of about 34 N/cm^2 and reported in reference 3.

The consistency of the temperature data shown in figure 4 is estimated to be within about $\pm$ 1 K for most of the thermocouples installed in the boiler. This consistency is the result of careful installation of the thermocouple wires and extensive in situ intercalibration tests conducted prior to and during testing of the boiler.

Boiler Overall Pressure Losses

A plot of the pressure losses across the boiler as a function of potassium flow rate is given in figure 5. These data were obtained during runs in which the potassium-exit pressure (exit saturation temperature) and the potassium-inlet temperature were held constant. The flow rate and the heat input were varied to achieve an exit quality of 1.0 and two levels of exit superheat. The pressure losses, as shown in this figure, are substantially larger for the boiler operating with a modest exit superheat. This increased pressure loss is due to the longer vapor path lengths present within the boiler tube and to larger momentum pressure losses.

Average Potassium-Boiling Heat-Transfer Coefficients

Figure 6 presents potassium heat-transfer coefficients averaged over the boiling (two-phase) region of the boiler as a function of exit quality or superheat for two exit saturation temperature levels of about 1255 and 1380 K. The data shown in this figure were computed from the temperature profiles of which figure 4 is an example. The average heat fluxes for the boiling region (excluding the liquid and, where applicable, the vapor-superheating regions) were estimated from the lithium temperature change and flow rate. The average inner tube wall-to-bulk potassium temperature differences were obtained from the shell temperature profiles and estimates of the lithium and inner tube wall thermal resistances.

The data of figure 6 indicate that the average coefficients are essentially insensitive to exit quality until an exit quality of about 1.0 is achieved. Thereafter, the coefficients decrease rapidly with increasing exit superheat. This behavior of the average boiling coefficient is attributed to the increase in length of the transition boiling regime with increasing exit quality and superheat. Descriptions of the heat transfer mechanisms occurring in boiling potassium are presented in references 3 and 4. These references may also be consulted for the effect of exit saturation temperature on boiling heat-transfer coefficients.

Transient Tests to Simulate Startup of the Advanced Rankine System

Transient tests were performed with the single-tube boiler to simulate the startup of the advanced Rankine system. These tests were based on the method employed to start the SNAP-8 mercury Rankine power conversion system as described in reference 5. In brief, the startup of the mercury system consists of two phases, a "bootstrap" and a "power" transient, separated by a time delay. Prior to the bootstrap transient, the reactor-coolant loop is brought to design temperature level by operation of the reactor at a reduced power. The mercury flow rate, during the bootstrap operation, is made to increase at a constant rate with time--i.e., a ramp increase--until a flow of about 50 percent of the design flow is achieved, about 100 seconds after commencement of the transient. Thereafter, mercury flow is held constant at the 50 percent value. During the ramp, the reactor control system acts to maintain the reactor outlet temperature constant by increasing the thermal power level. This bootstrap operation brings the power plant to a self-sustaining power level, a level which is maintained until transients in the reactor-coolant loop decay. Following this, a second mercury flow ramp takes place which brings the power plant to the design operating conditions. This second transient is 5 to 9 times longer in duration than the first and is a quasi-steady-state process.

For the potassium startup tests, both the bootstrap and the power transient phases were performed. The bootstrap transient is the more critical of the two for the power plant. One such test is, therefore, described below. The power ramp tests were similar to the normal facility transients which occur in changing from one operating point to another. Their performance offered no particular difficulty.

To conduct the bootstrap test, the lithium coolant was circulated at a temperature of about 1455 K, approximately 40 kW of thermal power being required to maintain this temperature. Liquid potassium at a temperature of about 720 K was admitted into the evacuated loop, filling the lower portions of the piping to a level well below both the boiler and the condenser. At the start of the test, the potassium pump was energized and the flow rate manually increased as a function of time until, after about 60 seconds, the value of the flow rate reached 0.02 kg/sec, about 50 percent of the design flow rate for the single-tube boiler. Thereafter, small adjustments were made to maintain this value. During the flow ramp and for about 60 additional seconds, the thermal power input to the lithium loop was manually increased to maintain the temperature of the lithium entering the boiler above 1450 K. Figure 7 presents the changes in potassium flow rate, boiler exit pressure, an insert temperature near the boiler exit, and power input to the lithium as a function of time during the 120 seconds of the simulated bootstrap test. As shown in this figure, no instabilities occurred during this severe transient. The facility could have operated indefinitely at the conditions achieved at the end of 120 seconds - that is, at conditions comparable to a self-sustained operation of the advanced system.

The insert thermocouple located near the boiler exit responded, as indicated in figure 7, about 38 seconds after the initiation of the transient. Approximately 35 seconds of this delay was due to the time required for the potassium to travel through the preheater and to reach the boiler inlet. This length of piping is specific to the test facility; consequently, such a long delay would not occur in the system startup. The effect of this delay was, in actuality, to make the flow ramp shorter in duration and, hence, the transient more severe.

The boiler outlet pressure increased 50 seconds after the start of the bootstrap transient. The pressure gauge employed to measure this variable has an estimated response time of the order of one second; therefore, the delay between the outlet pressure and temperature may have been due to the time required for the vapor to reach the condenser and for the pressure in this component to increase.

CONCLUDING REMARKS

A sampling of the experimental data obtained during performance and transient testing of a single-tube potassium boiler has been presented. Included was a temperature distribution within the boiler at fluid temperature and pressure levels closely matching those required to be met by the boiler of the advanced Rankine system. Overall pressure losses across the boiler as a function of flow rate for a constant exit quality of 1.0 and two levels of exit superheat were also presented, the latter pressure losses being substantially larger than the former. Potassium heat transfer coefficients averaged over the boiling region were shown to be very large, as large as 5 W/cm^2-K, at exit qualities up to 1.0. These coefficients decreased as the boiler was made to operate with exit superheat. Finally, the results of a transient test to simulate the startup of the advanced system were presented. Within approximately 120 seconds, the facility was stably brought to conditions which simulated a self-sustaining operation of the advanced system power plant. The data presented herein, a small fraction of the total obtained, alone indicate that a major advance in the technology of high-temperature liquid-metal space power systems has been made as a result of the successful testing of the single-tube potassium boiler.

NOMENCLATURE

$\bar{h}$	Heat transfer coefficient for potassium averaged over the boiling (two-phase) region, $W/cm^2\ K$
P	Potassium pressure, N/cm^2
ΔP	Overall potassium pressure loss across boiler, N/cm^2
Q	Net thermal power input to the lithium coolant, kW
$T_{K,O}$	Potassium temperature measured by thermocouple located within insert of boiler near outlet end, see figure 7, K
w	Flow rate, kg/sec

SUBSCRIPTS

i	Inlet of boiler
K	Refers to potassium fluid
Li	Refers to lithium fluid
O	Outlet of boiler
SAT	Saturation condition at boiler exit
SC	Boiler inlet subcooling
SH	Boiler exit superheat

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ACKNOWLEDGMENT

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TABLE 1. - RANGE OF VARIABLES FOR STEADY-STATE BOILER PERFORMANCE TESTS

Thermal Power Input Q, kW	60 to 185
Potassium Exit Quality X, and Exit Superheat ΔT_{SH}, K	0.5 to 1.0 0 to 167
Potassium Boiler-Exit Pressure P_o, N/cm^2	39 to 140
Lithium Boiler Inlet-to-Outlet Temperature Difference ΔT_{Li}, K	27.8 to 167
Potassium Boiler-Inlet Subcooling ΔT_{SC}, K	49 to 520

TABLE 2. - COMPARISON OF BOILER INLET AND OUTLET CONDITIONS AT THE NOMINAL OPERATING POINT OF THE ADVANCED RANKINE SYSTEM WITH THOSE FOR RUN SHOWN IN FIGURE 4

Parameter	Nominal Operating Point of Advanced System	Test Conditions for Run Shown in Figure 4
Lithium Inlet Temperature, K	1477	1456
Potassium Inlet Temperature, K	928	1039
Potassium Exit Temperature, K	1422	1423
Potassium Exit Pressure, N/cm^2	112	109
Potassium Exit Superheat, K	40	47.8

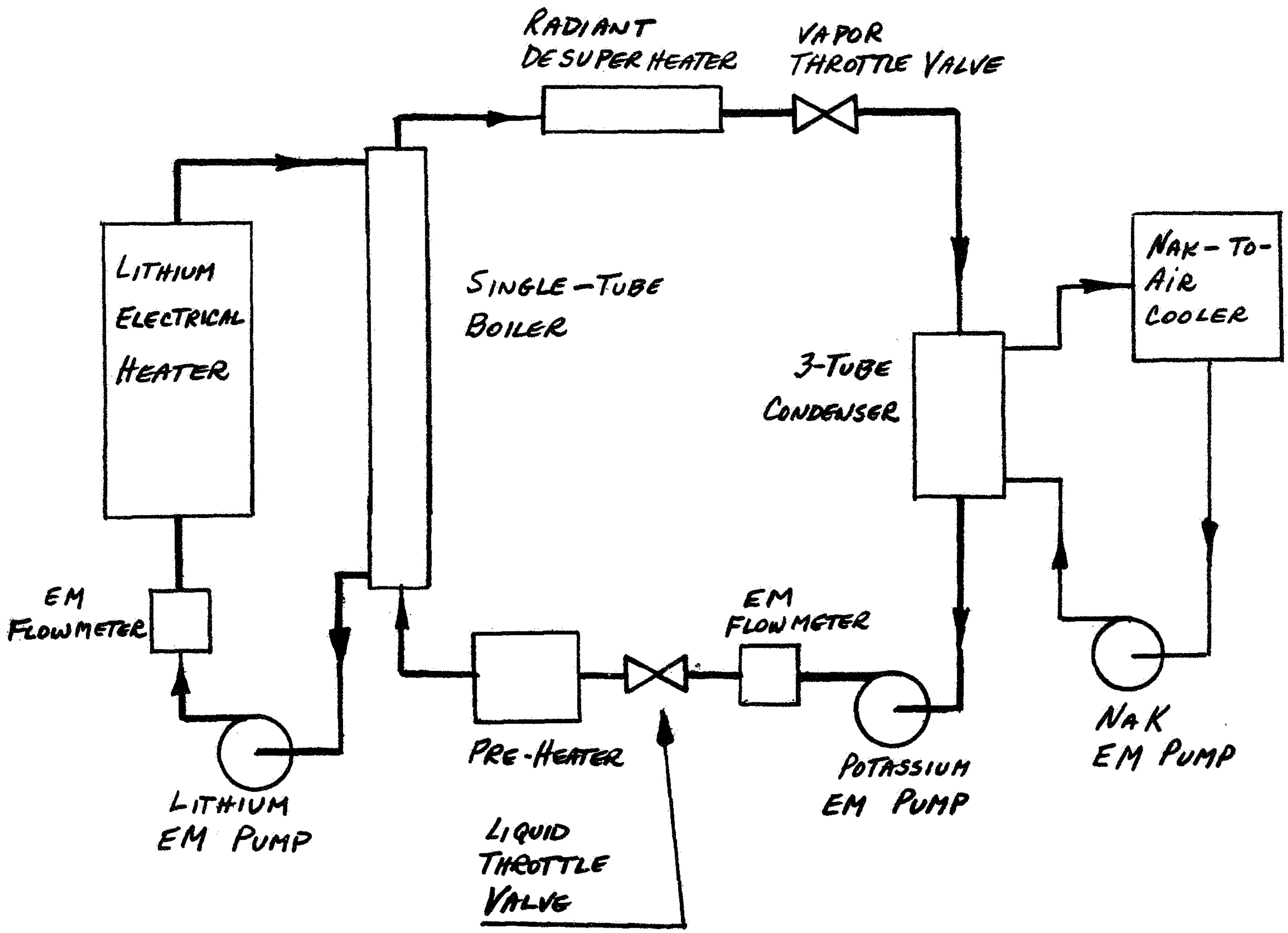

FIGURE 1. SIMPLIFIED SCHEMATIC OF TEST FACILITY

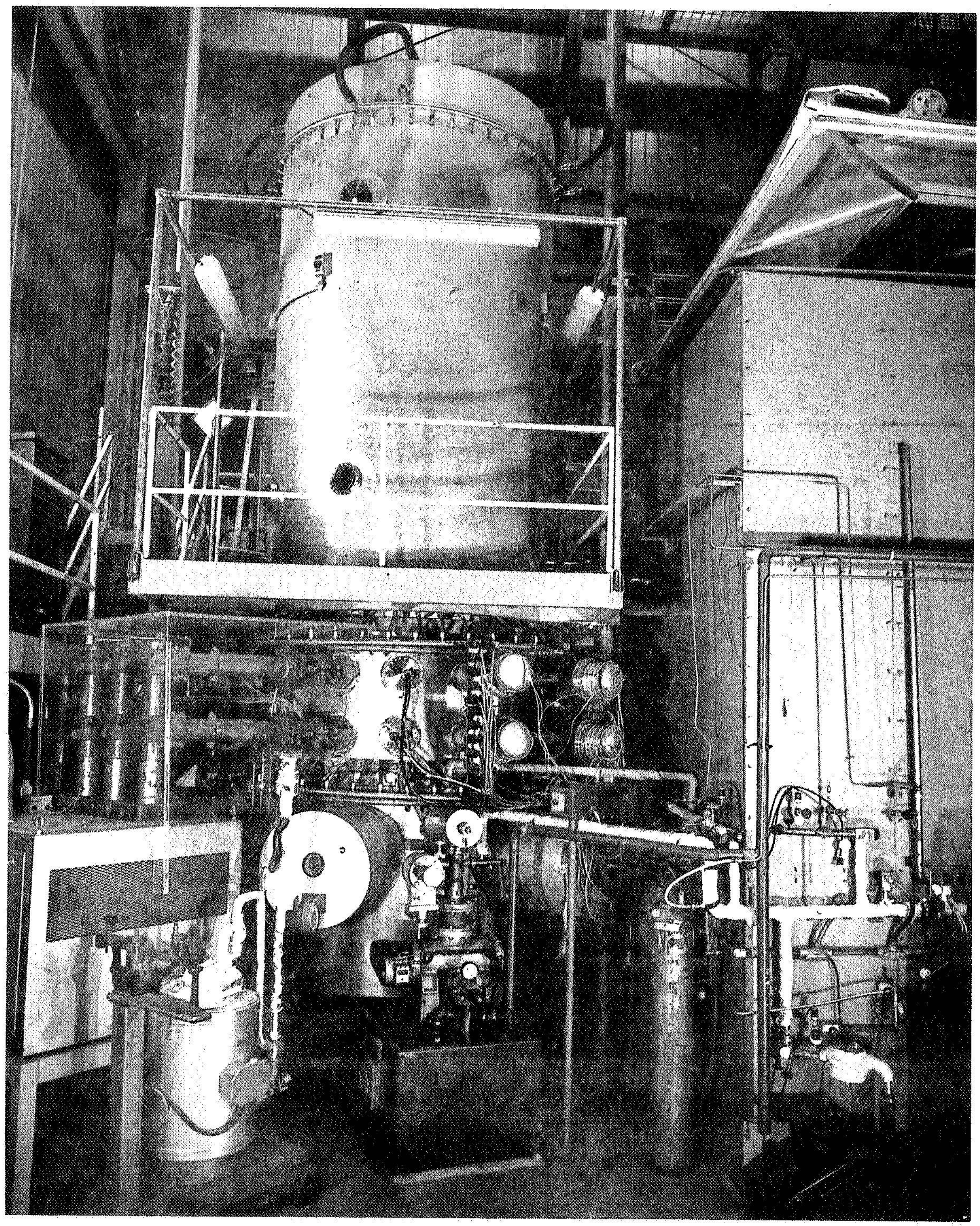

Figure 2. View of Test Facility Vacuum Chamber

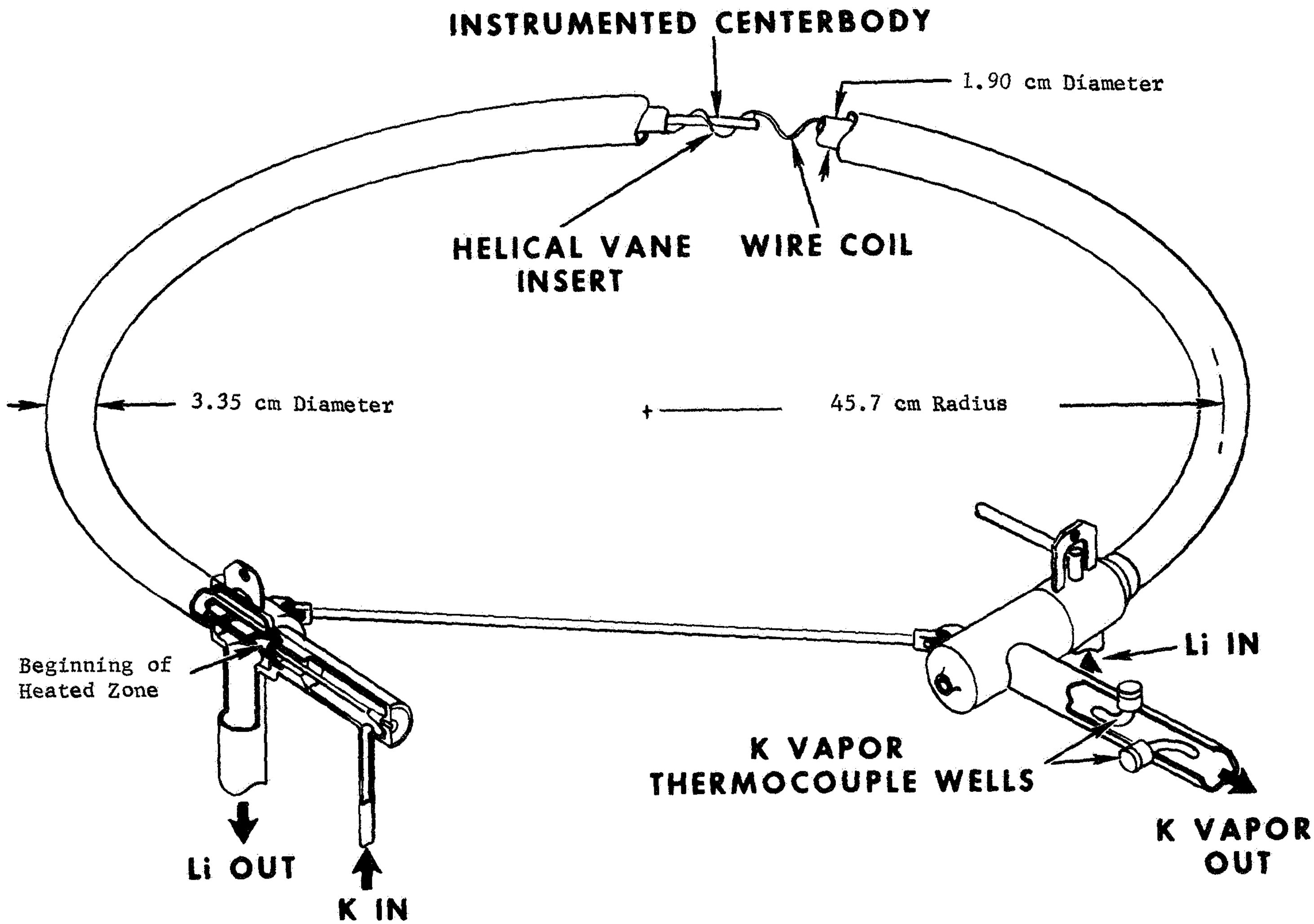

Figure 3. Schematic of Single-Tube Boiler

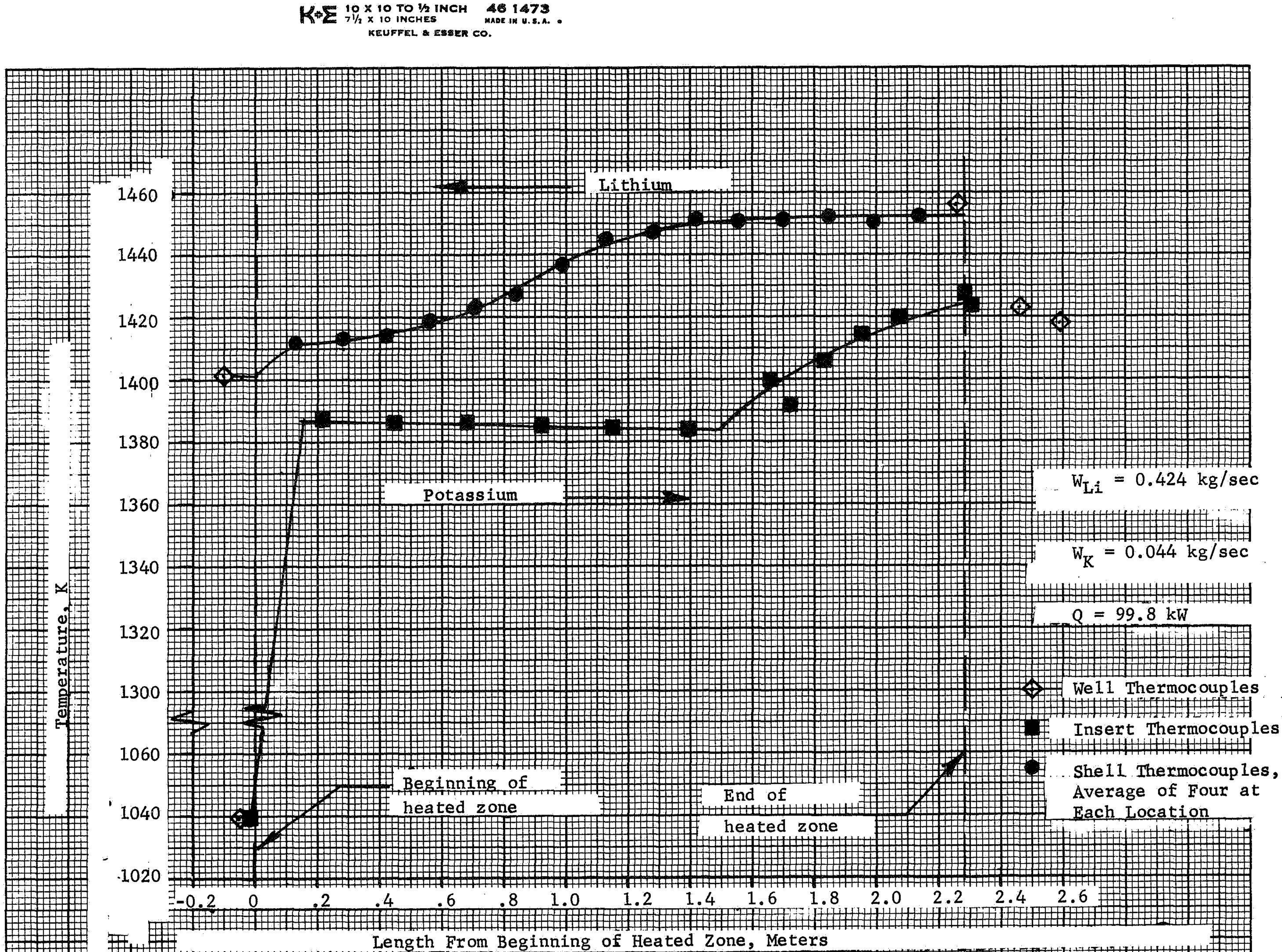

Figure 4. Boiler Temperature Distribution

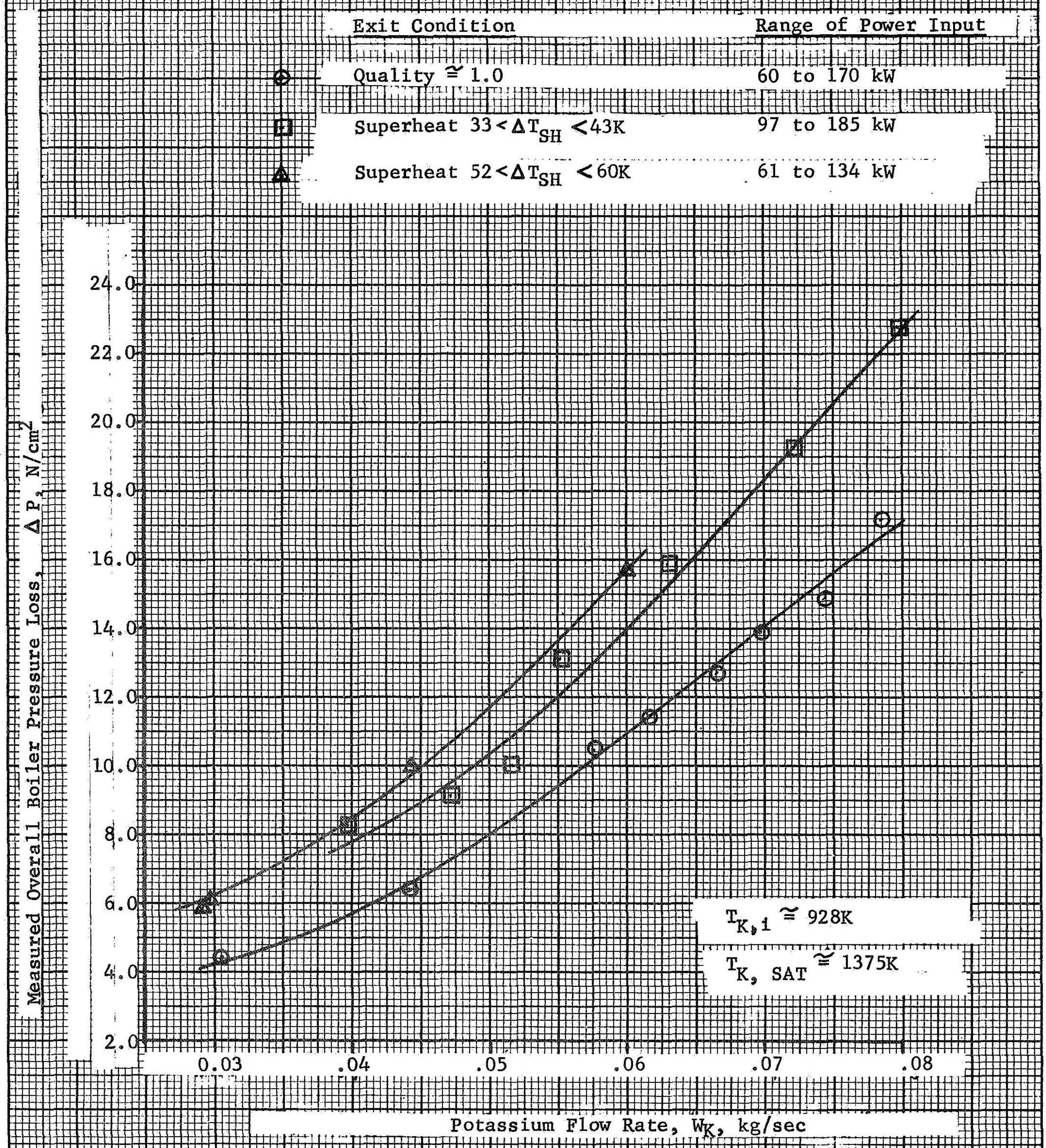

Figure 5. Effect of Exit Quality and Vapor Superheat on Boiler Overall Pressure Loss

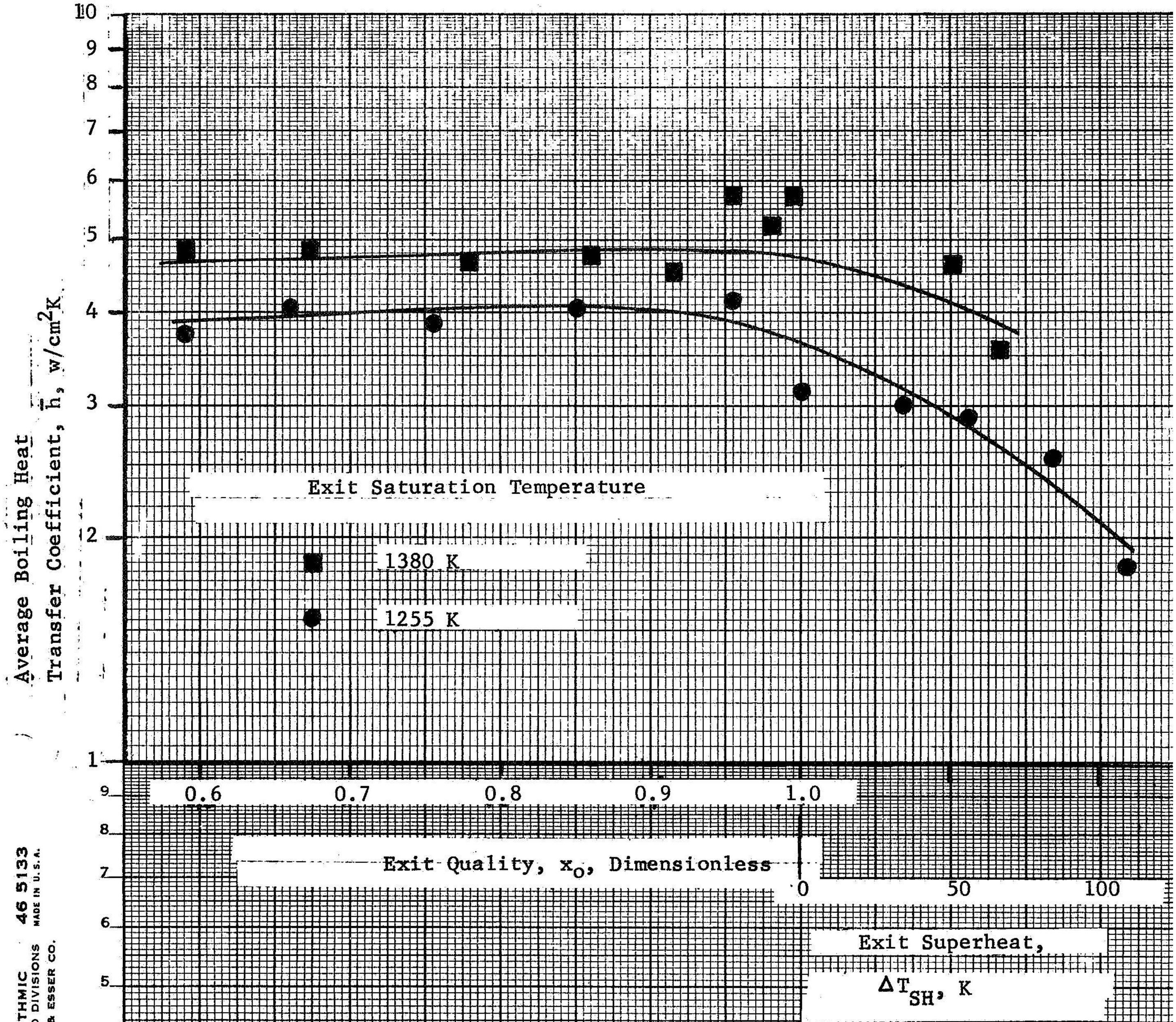

Figure 6. Average Potassium Boiling Heat Transfer Coefficients for Two Exit Saturation Temperature Levels (ΔT_{Li} = 55.6K, $T_{K,i}$ = 928K, Q = 87 kW)

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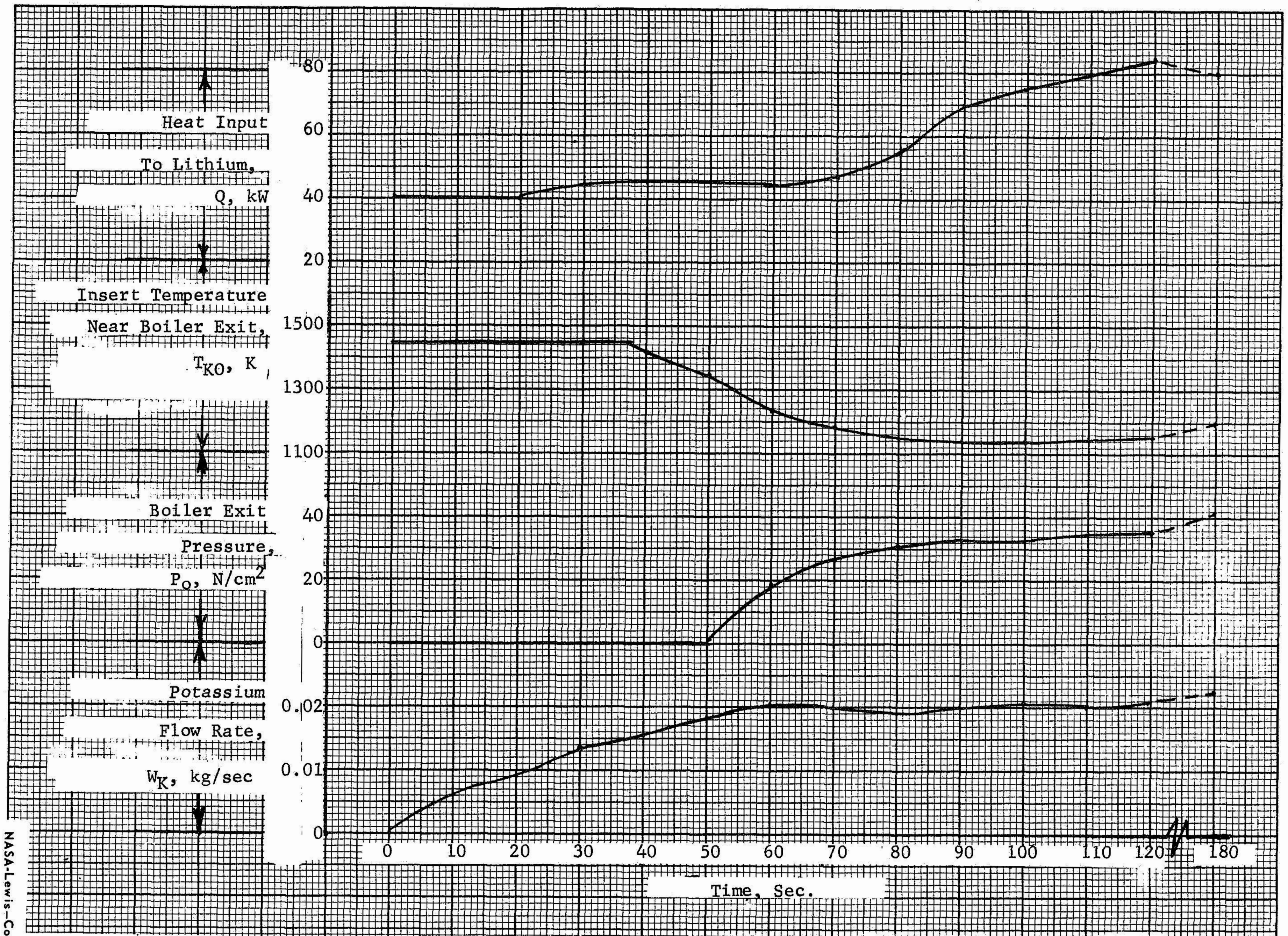

Figure 7. Behavior of Selected Parameters During Boiler Start-Up Transient

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